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STATE-OF-THE-ART SURVEY OF OIL-SPILL DETECTION, TRACKING AND REMOTE SENSING IN COLD CLIMATES

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STATE-OF-THE-ART SURVEY OF OIL-SPILL DETECTION, TRACKING AND REMOTE SENSING IN COLD CLIMATES

by

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ABSTRACT

The detection and subsequent tracking of the fate of marine oil spills in cold climates is afforded by recent technological developments, as well as judicious use of the human visual system. A variety of buoys is now available for following the progress of oil on water, or in an ice-infested environment. Active, radio frequency transmitters and navigational systems will keep accurate track of the progress of these buoys. Airborne and, to a certain extent, satellite-borne sensors can be used to probe for oil on or under the water, or entrained in, or trapped under ice. From the more conventional camera systems, to the more sophisticated laser, radar and acoustic sensors, each has its own advantages in determining the existence, measuring the spatial distribution, or defining the type of oil that has been released into the environment.

T.T. Alföldi
B.M. Sørensen

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1. EXECUTIVE SUMMARY

The development of methods for detection and tracking of marine oil slicks is essential for effective dealing with potentially dangerous oil-spill events. Slicks must first be found, sometimes in vast areas of ocean, and their movement must then be monitored accurately over time. Specific information on the location and distribution of oil is mandatory intelligence for crews tasked with clean-up or disposal duties.

In northern waters, oil-spill detection and tracking is additionally complicated by few and widely scattered facilities, extended periods of darkness in winter, and the presence of ice. Technology is pushed to its limits in efforts to cope with the many environmental complexities that influence the logistical handling of an oil spill.

To track the movement of an oil slick, one must detect it repeatedly and measure its location; or place a device, which would make its detection simpler, into or near the slick. The former method has been used most extensively to date, because of the very recent development of oil tracking buoys. Visual detection and identification has been, and continues to be the most popular form of (both detection and) tracking. From the surface and from an aerial vantage point, the human visual system is available, not complex, and very adaptable. It is also prone to error, unquantitative, and limited by weather and illumination levels. Subsurface oil can be seen only to a few metres in depth. Oil under or in ice cannot be detected visually; however, the ice in which the oil is entrained can be seen.

The current trend is to place buoys into a slick. These buoys are designed to react to water current and wind stimuli in the same way that an oil slick does, and thus to mimic the slick movement. Passive buoys would have heightened visibility to the eye, to radar, or to some other sensing device, in order to make repeat detection simple. This technique is subordinate to the use of active buoys, which carry a radio beacon or transponder and thus advertise their presence. Surface vessels and aircraft, which carry appropriate direction-finding radio receivers, could track the buoys. For aircraft, the effective range of detection would be 50 km or more. It is also possible to use navigation satellites to fix the position of a buoy on the Earth's surface.

For oil in an ice environment, the tracking process becomes the monitoring of ice mo vement, since the oil tends to move with the ice. Marine and airborne radars can easily record the ice motion. Special ice-tracking buoys can be placed (usually air-dropped) on the ice, and again, radio frequency techniques can be used to follow the buoy/ice/oil.

A variety of instruments has been used to address the problem of oil detection. No one instrument is suitable under all circumstances; the accepted approach appears to be an airborne platform carrying several remote sensing devices. The most popular sensor complement today is a side-looking airborne radar (SLAR), an ultraviolet and infrared (UV/IR) line scanner, and a film camera.

SLAR provides wide-area, all-weather, day/night search capability. It is restricted under very calm sea conditions and when the oil is in an ice environment. The UV/IR device offers two complementary detectors for defining the maximum extent of a slick, regardless of oil thickness (UV band), and the thicker regions of the slick only (IR band). The UV detector is limited to daytime operation, but the IR can operate at night as well. The IR has yet to

be proven, but has good potential for detecting oil on ice. The camera, meanwhile, records an image that is very similar to that seen by the eye, thereby providing a surrogate for a human observer.

Other remote sensing devices with particular applicability to oil-spill detection have been used successfully. The laser fluorosensor is most notable of these, due to its ability to detect reliably, as well as to classify oil into basic groupings. It is operable day and night, and may be used to find oil on, and possibly in, ice. The low-light-level television camera is used in an oblique viewing mode, often with a polarizing filter. It is simple, compact, and can be operated under low illumination levels, but not in darkness. Passive microwave radiometry can be used for oil-slick detection and thickness mapping. The measurement of attenuation by the surface oil of the microwaves emitted by the underlying water can provide accurate oil-thickness estimates for thick oil régimes. Multispectral scanners (MSS) operating in the visible and near-visible bands will record oil-slick features, as will a camera, but with finer spectral and radiometric resolution, and in a more quantitative manner.

Technology for the nighttime detection of oil slicks often plays on fluorescence phenomena. Most oils have a natural ability to fluoresce under UV excitation, so a lamp with a strong UV component makes a nighttime slick visible. Other methods being investigated include the doping of an oil slick with a fluorescing agent, which will selectively adhere to the oil, then fluoresce efficiently when illuminated by UV light.

It is also possible to detect oil slicks from sensors carried by satellites. Satellite platforms offer the advantage of repetitive, wide-area coverage at relatively low expense, due to cost sharing by all users of the system. Most satellite orbit and sensor

parameters, however, are not particularly suited to the demands of oil-spill detection. Usually a compromise is in effect between spatial and radiometric resolutions, and also between spatial and temporal (revisit frequency) resolutions. Yet, oil-slick detection requires high resolution simultaneously from all of these parameters. Timeliness of satellite data accessibility is another requisite which is not easily met, but critical to an oil-spill response team.

Oil on, in, or under an ice pack becomes a more difficult target for detection. On the ice surface, IR scanners, laser fluorosensor and passive devices working in the visible part of the spectrum may be used. Within or below the ice, detection requires new technology that is just now under investigation. Acoustic techniques (which are successful in detecting oil below the ocean surface) show promise in detecting oil that is trapped under ice, by means of discerning compression waves for which the viscous oil acts as a medium. Another area of research is examining the use of impulse radar for sub-ice detection of oil. Investigation of dielectric effects, insulation properties and interference phenomena related to oil may eventually result in the use of this instrument, which would be effective from aircraft, as well as from the surface.

2. INTRODUCTION

Marine oil spills can be reduced in frequency, but not eliminated, by improved technology and training of personnel. Oil exploration and associated activities in arctic regions, for example, are complicated by an inhospitable and often threatening environment. Therefore, oil-spill emergencies are to be expected, and most particularly in far northern areas.

In dealing with an oil spill, the prime requisite is to determine the geographic location of the spill, which also supplies a confirmation of the existence of the spill. Following initial detection of a slick, it is necessary to track its motion and monitor its physical/chemical state. This type of information is essential for subsequent activities of containment, recovery, and/or treatment.

Mapping of the slick in its three spatial dimensions provides essential information for recovering or treating the oil by identifying oil thickness régimes. Dispersant application or recovery operations can thus be directed to an optimum sequence of traverses of the slick.

The intent of this document is to survey the state of the art of oil-spill detection, tracking and mapping in the context of a marine oil-spill emergency occurring in a cold climate. To this end, both surface and remote techniques are included. Also described are directions currently being explored in research programs related to this topic.

2.1 TRACKING

Tracking of an oil slick can involve the repeated measurement of its distribution (relative motion) and geographic location (absolute motion). The latter is the more important of the two, and from it, speed and direction can be determined.

The dynamic motions of an oil slick can be followed by remote sensing methods, or by placing a tracking device into the slick. Airborne remote sensing is rarely used for continuous tracking, except during major disasters, due to expense. Sensing from satellite platforms is sporadic at best, and cannot be relied upon for tactical purposes. Tracking devices, usually buoys, are most popular due to convenience, economy, and continuous and all-weather operation, although they also have limitations. Passive tracking devices (such as floating radar reflectors) are the least expensive and simplest in nature; they also require the greatest effort to locate. Active tracking buoys are more complex and expensive, but are easier to locate and track. Modelling of the dispersion and movement of a slick may be an economical and convenient way to track an oil slick; however, any mathematical model of the real environment is only as good as the reliability of factors input to the model. For this reason, modelling excercises are usually prone to error, not because of the algorithms employed, but because of imperfect knowledge of the environmental conditions prevailing at the oil-slick site.

The marine environment plays a crucial role in determining the success of any technique for oil-slick tracking. Adverse weather, or the presence of ice is often the limiting factor in the performance of surface or remote tracking techniques.

For a general introduction to the topic of oil spills and the technology available to deal with them, the reader is refered to Fingas et al. (1979). An extensive bibliography on this topic has been prepared by Environment Canada (1981), while for remote sensing aspects, a suitable introduction will be provided by Thomson et al. (1980).

2.2 DETECTION AND MAPPING

Detection of an oil slick is necessary in order to be able to deal with the slick and its harmful effects. Unless a tracking device is placed into the oil slick at the time of the spillage, it may be necessary to search for and identify the slick itself. This can involve reconnaissance over very large areas and requires experienced observers and/or detailed knowledge of the interaction between an oil film and electromagnetic radiation. Surface and airborne techniques have been used for this purpose, and to a minor extent, even satellite imagery. Surface techniques have the advantage of closer, more direct contact being made with an oil target, but are severely limited in the speed and coverage of search. On the other hand, airborne remote sensing methods can investigate large areas quickly, but the indirect methods used for detecting oil phenomena require sophisticated instrumentation and data-analysis methodology for confident oil-target identification.

Visual methods have been, and continue to be used for oil-slick searching, but instrumented remote sensing is becoming more accepted and used worldwide, by various marine surveillance authorities. The complexities of searching in ice-infested or ice-covered water bodies has prompted research in a variety of areas, including the use of ultrasonics.

Mapping the distribution of an oil slick with reasonable accuracy is practical only with imaging sensors. All three spatial dimensions of a slick must be mapped, with the vertical dimension (oil thickness) being the most difficult, but also the most essential. The distribution of the thicker oil film régimes identifies the best targets for dispersant application, burning or recovery activities. Satellite imagery may be useful for mapping very large spills, but is severely restricted by low illumination levels, typically found in cold climates.

3. TRACKING

3.1 SURFACE OIL SLICK ON WATER

An oil slick on the water surface can be a very dynamic phenomenon, spreading, dispersing and moving under the influence of its own physical/chemical properties and those of the environment around it. The prime factors affecting slick movement are surface currents and winds. It is possible for a slick to travel at 10 km per hour or faster when driven by appropriate wind and current, which means a substantial daily displacement and an exponentially increasing area of search.

Past experience with oil spills has shown the need for rigorous tracking of slick movement. In the summer or 1970, an oil slick covering over 70 km^2 from the barge Irving Whale was "lost" in the Gulf of St. Lawrence, due to very dense fog, only to reappear unexpectedly on the shores of the Magdalen Islands (Ages, 1971). The Kurdistan incident of 1979 saw conflicting reports of small oil patches, large oil-slick areas and no oil, resulting in less than optimum action by the responsible agencies. These and other oil-spill events have prompted much research and development of slick tracking devices and techniques, with which to provide basic information on slick location.

3.1.1 Visual Methods

Visual observation has long been the most widely used method of marine oil-spill surveillence. Despite subjectivity and propensity for error, people tend to have confidence in the information collected by their own senses. Most tracking exercises involve the repetitive sighting or detection of a slick, so it is the detection and identification of a slick that is critical in the tracking process.

To the eye, the appearance of an oil slick is extremely variable, depending on illumination conditions, oil type and thickness, relative locations of the slick and the observer, environmental conditions prevailing at the time, and the physical and mental state of the observer. Even under ideal conditions, the water-to-oil contrast is subtle in the visible portion of the spectrum, straining anyone's visual acuity. Fingas et al. (1979) provide colour photographic examples of the appearance of oil on a calm water surface. Varying oil thicknesses show on camera as "barely visible" (about 0.04 μm thickness), "silvery sheen" (0.08 μm), slight colouring (0.15 μm), stronger colouring (0.3 μm), dull colours (1.0 μm) and dark colours/opaque surface (2.0 μm). The authors also show colour photographic representations of the appearance of several oil types, 1 min and 24 hr after spillage. This document has numerous illustrations of actual oil spills in the environment, providing the reader with an appreciation of the complexity of the phenomenon.

The aerial vantage point for tracking oil is particularly important, since effective surveillance cannot be accomplished on the sea surface. An airborne observer, however, must contend with the additional complications of viewing the water surface through varying degrees of haze, from an unstable platform, and with changing illumination and reflectivity conditions. Specular reflection of the sun on the water surface can mask the presence of a slick, or alternately, enhance it if the viewing geometry is just right.

The view of actual marine oil slicks and the problems of visual identification are well demonstrated in a brief technical note by the International Tanker Owners Pollution Federation (1981). Colour photographs illustrate oil slicks under varying degrees of emulsification and weathering, and influenced by wind and waves. Some common, false oil-slick targets are also presented: cloud shadows,

seagrass and (inorganic) suspended sediment. In addition, the document offers advice on search patterns, visibility aids, and a guide for estimating oil thickness (Table 3.1).

The availability of sophisticated sensing devices has not obviated the use of human observers. Indeed, in at least three recent oil-spill disasters in which sensor-equipped aircraft were sent to track the slick movement, visual sightings and identification of the slick were relied upon prior to activation of the sensors. During the AMOCO Cadiz disaster in the spring of 1978, an aircraft from the Institut Géographique National (France) was tasked with reconnaissance of the oil spill (Fontanel, 1979). The aircraft carried two photographic cameras and a thermal infrared (TIR) line scanner, which were used to record details of the slick after it had been located and identified by visual means. Similarly, in the Kurdistan incident in early 1979, visual observation by search aircraft personnel was depended upon to detect and identify oil targets. The Canada Centre for Remote Sensing (CCRS) aircraft, which were deployed for oil-slick surveillance at that time, carried a variety of scanning devices and cameras that were activated following visual recognition of an oil target (O'Neil et al., 1980b).

Following the IXTOC-I oil well blowout in the Gulf of Mexico in mid-1979, the U.S. Coast Guard (USCG) conducted surveillance of the movement and state of the resulting oil slick. The relative importance of human observation versus mechanical equipment is clearly indicated in this extract from a USCG report: "Low altitude visual aircraft reconnaissance backed up by an all-weather airborne remote sensing system . . . proved to be the most effective tactical and . . . strategic aid for environmental pollution response planning . . ." (Hayes, 1980).

Table 3.1 A guide to the relation between the appearance, thickness and volume of floating oil (Source: ITOPF, 1981)

Oil Type	Appearance	Approximate thickness	Approximate Volume (m^3/km^2)
Oil sheen	silvery	0.0001 mm	0.1
Oil sheen	irridescent	0.0003 mm	0.3
Crude and fuel oil	black/dark brown	0.1 mm	100.0
Water-in-oil emulsions ("mousse")	brown/orange	1 mm	1000.0

Nor is visual observation being phased out as an oil-slick detection and tracking methodology. Rather, modern technology is seen to complement and assist the observer. At a NATO-sponsored international meeting in 1979 on the Airborne Remote Sensing of Oil Spills in Coastal Waters, the technical panel tasked with identifying a ". . . core package of sensors for the detection and mapping of oil pollution . . ." (O'Neil et al., 1981) placed the human observer prominently on its recommended list of sensors.

The human visual system is a very flexible tool; however, there are some techniques and devices available for enhancing oil-detection capability. The foremost of these is experience, followed by the observer's thorough understanding of the physics of light interacting with an oil film. Nothing can supplant these. In addition, however, the expert observer can take advantage of certain viewing geometries, colour filtration, and polarizing of the incoming radiation.

3.1.2 Passive Devices

Tracking of surface slicks by means of passive devices requires the placement of a device into or near a slick, and then the monitoring of its progress by means of some sensor. The device must meet two important criteria. First, it should respond to wind and current the same manner as oil does, such that it mimics the movement of an oil slick. This requirement is the most difficult to meet; to date it has not been achieved completely because the mobility of oil in the marine environment is not perfectly understood. The second criterion specifies that the device should be more easily detected by some sensor than is the oil target itself, to enhance the possibility of finding the adjacent oil.

A variety of ingenious oil-slick (passive) trackers have been used in oil spills. The range covers conventional buoys and drogues, to sheets of plywood, blankets of bubble-cap plastic,

computer cards and hula hoops. Each of these attempts to present a low profile to the wind, as does an oil slick; this is, of course, counterproductive in a way, since it reduces visibility. Still, the achievement of simulated oil-slick movement is a priority. The frustration of designers of oil-slick buoys is best expressed by Ages (1982): ". . . almost any floating object with a draught of a few centimetres will at one time or another stay with an oilspill; and at one time or another wander off on its own. Even an oilspill itself rarely retains its cohesion but moves about in streaks and patches several kilometres apart." Ages notes another complication: "As its specific gravity increases due to emulsification and evaporation, any type of oil will eventually sink below the sea surface and move at a slightly lower velocity."

Enhanced visibility of a buoy or float is usually achieved with a bright and strongly coloured appearance, which makes it more easily detectable by eye, or some artificial sensor that is sensitive to the visible portion of the spectrum. A fluorescent paint can be used as well (Bannister et al., 1982), and will be better observed when illuminated by a natural or artificial -- typically ultraviolet — light source. In the microwave region, an omnidirectional corner reflector is commonly used to achieve a strong point source return to an active radar sensor. The reflector, however, must be well exposed above the sea surface in order to be detected; yet that configuration is detrimental to oil-slick-like response to wind stimulus.

The compromise between using active and passive oil-slick trackers is related to where one wishes to expend energy and funds. A passive device is more easily and cheaply constructed, and its utility is more dependable and longer lasting. Its detection or monitoring, however, requires sophisticated sensors and close proximity between sensor and tracking device. Thus, more expense must be committed to the search process for sensors and flying time.

Active tracking devices (which commonly employ some form of radio communication) are more expensive to construct, are more prone to malfunction, and have a shorter useful life. The search/monitoring process, however, is much simpler than for passive devices, since normal radio tracking equipment can be used and detectability is at much greater ranges. The search/detect process, therefore, is an easier and cheaper task.

3.1.3 Active Devices

The trend today appears to be towards the use of active, rather than passive oil tracking buoys. Despite their increased complexity and cost, the overriding costs for deploying any buoy into an oil slick dictates that the tracking device must be successful in its task, as possible.

Considerations for tracking buoys (active) can also be broken into two aspects: movement and detectability. As with passive buoys, the ability of the device to copy the movement of an oil slick is the most difficult technical problem, yet the most important. While a simple model such as: Oil drift = sea current + 0.03 wind (all vector quantities [Parker and Cormack, 1979a]) is a buoy performance to strive for, actual oil mobility is much more complex.

Ages (1982) gives a treatment and experimental data for this problem. His and his colleagues' work has had significant influence on the development and subsequently successful marketing of oil-spill tracking buoys by two Canadian companies: Orion Electronics Ltd. of Nova Scotia, and Novatech Designs Ltd. of British Columbia. Additional research on oil-slick buoy architecture and performance is being conducted at the Bedford Institute of Oceanography in Nova Scotia. Bedford's approach is to construct a new (reference) buoy, against which the performance of any other buoy or floating device can be assessed. As well, the results of Bedford field trials may be used to improve on current buoy designs, or to construct a new prototype.

Detection of these drifting buoys is by radio transmission/reception. Although detection and location could conceivably be accomplished from polar orbiting (or geostationary) satellites, today's commercially available systems (Orion, 1983; Novatech, 1983) presume a ship-borne or airborne search procedure, using VHF radio frequency tracking, or a range and bearing transponder system. These devices are typically air-drop-rugged, can function under arctic conditions, and have a range of 50 km or more to a detector carried by an aircraft.

Field trials of commercially unavailable oil-slick tracking buoys were held in late 1976 (Fingas, 1977) and in 1981 (Roddis, 1982; Fingas and Lea, 1981; Lea, 1981). While the results from one of the three types of buoys were inconclusive, the other two showed good ability to move with the oil slick, with very little deviation. These Canadian buoys have not only been used in North America, but are also popular in Europe where, for instance, the Swedish Coast Guard uses them operationally (Sørensen, 1983).

There is an extensive network of spill-related research in Europe (see Appendix A), and several organizations have conducted experiments with Canaidan and/or in-house oil drift buoys. Buoy development has been conducted by agencies such as the Danish Hydraulic Institute, Institut Francais du Petrole, Deutsche Hydrographisches Institut, Warren Spring Laboratory (U.K.), University of Dundee (Scotland), Rijkswaterstaat (Netherlands) and the Christian Michelsen Institute in Norway (Sørensen, 1983; Hammer et. al., 1982). Other active oil-slick tracking methods that have been, or are being investigated by European agencies include an active radar reflector, triggered by an electric pulse in the microwave region and a flash lamp mounted on a buoy. The latter technique has not been very successful.

3.2 SUBSURFACE AND DISSOLVED OIL TRACKING

Oil will sometimes settle into the water column in a dissolved state, or intact if its specific gravity has risen to equal or exceed that of seawater. Without a surface expression of the oil, tracking must rely on devices that are linked to the subsurface oil movement, or can penetrate water and identify the presence of the oil directly.

The former method would probably use a buoy with a drogue attached at a depth representative of the submerged oil. The oil would move exclusively as a result of stimuli from water currents at that depth, and so, presumably, would the buoy/drogue. Again, the problem in designing such a buoy would be to remove any influence of wind, wave and surface currents on buoy movement, and yet permit easy tracking of the buoy. There have been no experiments of this type described in the open literature for tracking oil spills, although many researchers, worldwide, have worked with the tracking of subsurface ocean currents per se.

There are several devices with potential for detecting subsurface oil directly. These include cameras, laser fluorosensor, (visible band) scanners, TV cameras and acoustic sensors. It may even be possible to identify oil by visual observation, or by satellite-borne sensors under favourable "viewing" conditions. All sensors working with electromagnetic radiation will be limited in ability of oil detection when that radiation must traverse the water column twice (downwelling, then upwelling). The greater the depth of the oil below the water surface, the more unlikely it is that it can be unequivocally identified by any sensing device.

The technology available for the tracking of subsurface oil movement is still in the realm of research for oil "detection". As such, it is detailed in Section 4.2 of this review.

3.3 CONTAMINATED ICE TRACKING

The surveillance of an oil slick in the presence of sea ice is complicated, due to the masking effect of the ice. Oil under, or in ice is particularly difficult to detect or track directly. Ice will block visible radiation, preventing all but oil on the ice surface to be seen by the human eye, or with aerial sensing devices using the visible bands. In the microwave region, the sea-clutter suppression feature of oil is no longer valid for imaging oil. Ultraviolet and TIR radiation will also be blocked or severely attenuated by ice.

After the location of the oil has been determined, the problem of tracking oil in an ice-covered or ice-infested area becomes an exercise in tracking ice, since the oil will "link" itself to the ice, and will move at the same speed and in the same direction as the ice. Thus, airborne sensing techniques or radio tracking buoy methods for tracking of slicks actually address the technology of ice tracking.

3.3.1 Aerial Sensing Methods

Very little experience has been gained in the tracking of oil-contaminated ice. The event that has provided most existing experience on this topic has been the Kurdistan incident off Nova Scotia in March 1979. This oil spillage from a tanker ship resulted in the contamination of near-shore ice in Gabarus Bay, Cape Breton Island, and of offshore ice as well. The oil mixed with the loose, broken ice, or lying on (and in) the densely packed near-shore ice, was observed from the surface (Reimer, 1980), from aircraft (O'Neil et al., 1980b), and from satellite (Dawe et al., 1981; INTERA, 1982a).

With each of these methods of surveillance, the exercise dwelt on the problems of oil detection and identification, which is a prerequisite to tracking of slick motion. Tracking *per se* came about incidentally, by noting the observer's location, or the position of the aircraft during imaging. Details on the means of detection of oil in an ice environment, with special reference to the *Kurdistan* incident, are contained in Section 4.3.

Most airborne remote sensing devices in common use can image ice in contrast with an ocean background, and some can differentiate among various ice categories. A few such instruments even have potential for detecting oil in, or under ice (Section 4.4). The most practical method, however, for airborne mapping and tracking of ice (and the associated oil) is by means of side-looking airborne radar (SLAR). "Practical" and "economical" labels apply to ice reconnaissance by airborne radar, due to its ability to image very large swaths (50 km or more on each side of the aircraft) of the Earth's surface, to be operable day or night and even in adverse weather conditions (Citizen, 1982). Indeed, the technology is considered "operational" (Bullock et al., 1982), since it has been a regular, commercially offered service in the Arctic for some years, supporting drilling operations at marine sites.

Both real and synthetic aperture radars (SARs) can be applied to the task of tracking (oil-contaminated) ice. The latter provide higher spatial resolution through coherent averaging of the return signal, while the simpler data handling of the former makes for significantly lower equipment costs.

The tracking process involves imaging the ice at two or more times, and determining its location for each recorded image. There are several techniques used for improving the success and accuracy of this process. By deploying corner reflectors at critical locations in an ice pack or on icebergs, target detectability is greatly enhanced

and, as well, control points are established for subsequent ice-motion analysis. Use of a precise inertial (or other) navigation system (INS), linked to the radar image recording apparatus, will produce better information on ice location. Image processing can also play an important role; optimum image display and enhancement, linked with a convenient multi-temporal analysis algorithm (Inkster et al., 1983), can greatly accelerate the entire data-reduction procedure.

Another consideration in a tactical, fast-response situation during an oil-spill emergency is the use of a (radio) downlink from the aircraft to the on-scene commander in charge of the spill response team. This technology, already proven for ice reconnaissance, can cut through normal delays in aircraft transit times and radar image processing by putting the radar imagery of the (oil-contaminated) ice in the hands of the decision makers, in real time.

3.3.2 Radio Tracking Buoys

An alternative to remote sensing for tracking of oil-contaminated ice is the use of active (homing) buoys attached to the ice. Since these devices are placed on, or into the ice, there is no question of their ability to duplicate oil motion, as there would be with floating buoys. Both the oil and the tracking device follow the ice movement, which is controlled by wind, current and the Coriolis force. The parameters of concern, therefore, relate to methods of delivery of the buoy to the target and the radio interrogation/activity of the buoy.

In a review of this technology, Goodman (1978) suggests that ice-tracking buoys should have a useful life of 10 months in an Arctic environment. He indicates the airborne drop as the preferred method for placing a radio buoy on a remote site, and identifies the hard drop (missile-shaped buoy penetrating the ice surface) and the soft drop (parachute deployment of buoy to the ice surface) as the two

main alternatives, with the former being more favourable. Blackall (1978) analyses the question of hard versus soft drop for ice-tracking buoys, and decides in favour of the soft landing system.

Goodman (1978) also describes methods currently available for determination of buoy position by satellites. Polar orbiting satellites, because of their motion relative to a buoy, can employ Doppler techniques to fix the location of a transmitting buoy on the Earth's surface. With some reasonable assumptions of anticipated buoy trajectory, the buoy can be located through information from a single satellite overpass. Alternately, two satellite passes will be sufficient to provide unambiguous positioning of a buoy. The accuracies achieved with a popular system, such as ARGOS, are of the order of a few kilometres.

Geosynchronous satellites, which have a fixed position relative to the Earth, cannot use Doppler position methods for measurement of ice movement. They are typically used for data retransmission from remote platforms. Goodman indicates that, by employing a global positioning system (such as OMEGA or NAVSAT), a remote ground station can determine its precise location (with an accuracy of the order of 100 m) and transmit this information via a geosynchronous satellite.

Drifting buoys with radio beacons can also be tracked from shore or from aircraft. Land-based receivers can use standard radio ranging methods to triangulate the position of an offshore buoy. Limited range, distortion from atmospheric effects, and maintenance costs are cited (Goodman, 1978) as the major drawbacks. Still, such systems are being produced commercially in Canada. Roddis (1982) describes one such device in detail, as well as its performance during tests in the Beaufort Sea and off Nova Scotia.

Tracking of radio beacon buoys is very practical from aircraft. A direction-finding antenna on a search aircraft is used to locate the beacon from a range of 10 km to 50 km. Limited range and radio interference (in the high-frequency [HF] band) are possible constraints.

A major testing program for air surveillance of ice-tracking radio buoys was conducted in the Beaufort Sea in the spring of 1981. Hill (1981) reported a successful experiment with typical buoy-detection ranges of approximately 30 km, and a notable improvement over simple, visual reconnaissance from the air.

4. REVIEW OF THE DETECTION AND MAPPING OF OIL SPILLS

The need for a system to detect oil spills may not immediately be obvious, yet this requirement has been demonstrated many times over. Small and large, surreptitious discharges of oil and oily fluids occur daily in Canadian waters. As well, accidental oil spills occur occasionally. In order to identify the location, extent and movement of an oil slick — all of which are essential to cleaning up or treating the slick — a reliable and quantitative method is required for oil detection and mapping. An insight into the applicability of a spill-detection system may be obtained from a list of the services provided by a conceptually "ideal" system:

- provide continuous, day and night, all weather, wide area, real time surveillance.
- detect any oil spill that occurs in the marine environment both on and below the surface.
- confirm that the detected substance is in fact oil.
- map the areal extent of the spill.
- obtain the thickness distribution and quantify the amount of oil spilled.
- identify the source of pollution and the specific type of pollutant being discharged.
- provide precise navigational accuracy for spill and source location and positioning clean-up vessels.
- document all collected data on hard copy records for legal evidence. (O'Neil et al., 1981)

The above system performance design is so versatile that only a multi-sensor approach can hope to approximate its total capability.

In evaluating any sensor or mechanism for oil detection, the performance of the device can be categorized for increasing sophistication (or success in oil detection) as being able to: 1) detect an oil-like artifact; 2) identify it as oil; and 3) determine the type of oil. The detection of a feature on the water surface, which may be an oil slick, is the most simplistic form of detection, but also the most valuable. Most of the time and effort expended on oil surveillance is devoted to locating these features. Once their location is established, much less time is consumed to determine their nature (i.e., separate the false targets from true oil slicks).

A device that can locate and identify a marine feature as an oil slick provides an even more valuable service than one that is susceptible to false targets. No remote detection device is completely accurate, but some give a greater degree of confidence than others, due to their ability to discriminate among target types. When this performance is even more sophisticated, a sensor may be able to identify certain groups of oil types. This information is valuable for choosing the most appropriate method for clean-up or treatment of a spill, and for tracing the origin of a slick.

Another very useful feature for an oil-detection device is the ability to image or map the areal distribution of a slick. Most remote sensing devices, except for profiling instruments, can accomplish this to some extent. If the device is also sensitive to oil-thickness variation, then it can generate three-dimensional information on oil thickness versus areal extent.

4.1 SURFACE OIL ON WATER

4.1.1 Surface Methods

Surface surveillance of oil spills is not the most practical method for investigating large areas quickly, yet often in the past, it has been the method of detecting marine oil spills. Surface observation is hindered by lack of mobility (compared to an airborne platform) and by an oblique view of targets on the water surface. Its main advantage is in proximity of observer (or sensor) to the target, which results in confidence of observation and the possiblility of taking direct samples from the water.

By its very nature, direct observation is subjective, and therefore, affected by human foibles. It also depends upon a variety of environmental parameters, such as sea state, weather conditions, illumination geometry and intensity; and the nature, quantity and distribution of the oil.

In a widely used report, Hornstein (1972) describes a series of empirical tests and theoretical calculations for defining a relationship between oil film thickness and appearance. He concludes that the relationship is real, and also is independent of oil type and water type. In suport of his thesis, he states that: "a) The two principles of reflectivity and interference adequately explain the quantitative as well as qualitative appearance and visibility of oils films less than 3000 nm thick. b) No other phenomena need be invoked to explain these findings." (Hornstein, 1972)

Hornstein identifies colour as the primary aspect to be used by an observer in estimating oil film thickness. He describes in detail the oil thickness/appearance relationship (Table 4.1), and his schema is used extensively for oil identification and thickness estimation by agencies such as the Canadian Coast Guard (CCG).

Table 4.1. Schematic basis for thickness-appearance relationship (Source: Hornstein, 1972)

Appearance	Thickness Range (nanometers)	Description
Colorless Films	Up to 150	Films reflect more light than does water, and look brighter. May need adjacent bare water for comparison. Apparent brightness increases with thickness. At about 75 nm and thicker, a pearly or metallic luster is usually apparent.
Onset of Color	Approx. 150	First color seen is a warm tone, more bronze than yellow. As film thickens, deep violet or purple appears, these colors begin the first set of rainbow bands.
Pure Rainbow Colors	150 to 900	The set of bands around 300 nm are in the sequence: bronze, purple, blue, green, in order of increasing thickness. These colors are pure and intense. The set of bands around 600 nm are slightly less intense than at 300 nm, and have a modified color sequence: yellow, magenta (reddish violet), blue, green. They are quite pure.
Dull, Impure Colors	900 to 1500	Main characteristic is reduction in number and purity of colors. Colors at 900 nm are a rich terra cotta (brick red) and turquoise (rather bright blue-green). At 1200 nm and 1500 nm these colors are progressively duller or less pure looking. These sets of bands may also contain a trace of white or pale yellow.

. . . /continued

Table 4.1. Concluded.

Appearance	Thickness Range (nanometers)	Description
Light and Dark Bands with Little Color	1500 to 3000	Any color present is merely a tint in the light and dark alternating bands. At 1800 nm, the contrast between light and dark bands is strong, but weakens as thickness increases. At 3000 nm, it is apparent that interference effects are weak, and they will quickly disappear as thickness increases.

An obvious shortcoming of direct observation of slicks is the lack of performance at night. Two novel approaches to this problem have addressed the fluorescence phenomenon as a solution. The Environmental Emergencies Branch, Environment Canada has worked on an illumination device (Fingas, 1982) that exploits natural fluorescence properties of most oils. The lamps used have a high ultraviolet content, which is readily absorbed by the oil in the illumination path. Upon "de-exciting", the oil emits visible light allowing detection by eye under constraints of distance, illumination power and ambient illumination (target/background contrast). Based on empirical tests and further calculations, Fingas suggests that the practical, maximum detectable distance can be as much as several tens of metres, depending on oil type and background illumination.

Another group of researchers (Bannister et al., 1982) artificially enhances the fluorescence-induced (nighttime) visibility of oil by adding a highly efficient fluorescing agent to the oil. The fluorescing agent is preferentially retained by the oil, but dissipated by water. Some testing has been conducted on this technique, using ultraviolet lamps and observers on a ship, with visible fluorescence effects reported at a distance of approximately 10 m. Future experiments will endeavour to detect surface oil doped with fluorescing agent at several times that distance, and use an airborne delivery system for the fluorescing agent.

The conventional marine radar (mounted on a ship's superstructure) is a promising device for oil-slick reconnaissance, because it is widely available, has a better range of detectability than direct observation, and is operable day, night and in adverse weather. Its most serious limitations are lack of target (oil-to-water) contrast in very calm sea conditions, target masking in the presence of ice, and an effective range of about 10 km. Special data processing methods (INTERA, 1983), however, can improve target definition and range.

Several *in situ* devices for oil-spill detection are described by Klemas (1971), for use in areas where spills are probable: harbours, refineries, loading docks, etc. An oil-thickness monitor, based upon a floating capacitor, can detect oil unambiguously and measure its thickness in a range of 0.5 cm to 1.3 cm. It is not suitable for thinner oil films, or for use in turbulent water. A floating planar reflectometer uses the higher reflectance of oil versus seawater, which results from the oil's higher refraction index, to detect a possible oil slick. This device can be confused by substances other than oil. More exacting techniques are available through machinery that extracts samples from (say) refinery effluent, and then performs ultraviolet absorption spectroscopy. These devices are, of course, in limited use due to power, weight and space requirements, and because of high costs.

Several devices intended more for field deployment are offered by the Institut Français du Pétrole (see Appendix A). These are buoys, free-floating or anchored, some with air-drop capacity, which are used for one-time detection of oil. Their operating principle is based on a fuse, which is stable in water and normal atmospheric constituents, but is highly sensitive to most hydrocarbons. Various oil and gasoline products will dissolve the fuse in a matter of minutes or seconds. Once the fuse dissolves, a radio signal is sent, or modulated to indicate that oil has been detected. Depending on the buoy model, a visible, flashing light or radar reflector can complement the RF transmitter (Sørensen, 1983.)

4.1.2 Airborne Methods

Marine surveillance for oil spills is very limited for surface vessels, due to the restricted areal coverage of search per unit of time; while from satellite platforms, the low frequency of overpass and few suitable sensing instruments makes orbital

reconnaissance impractical. Airborne observation, however, is very applicable to this task, and most agencies with a mandate for marine surveillance have grasped this technology.

Physical phenomena in various portions of the electromagnetic radiation spectrum are commonly used to deduce the presence of oil on the water surface, by means of aircraft-carried sensors and human observers (O'Neil, et al., 1980). In the visible and near-visible (ultraviolet, reflective infrared) bands, complex interactions of reflection, absorption and scattering effects on radiation, from clear water versus surface oil, produce distinctions betweeen these two targets. In addition, thin oil films can produce interference effects and alter the polarization characteristics of the reflected illumination. Other radiation phenomena in the (near-) visible spectrum that can yield a positive indication of surface oil, include characteristic fluorescence, filling in of Fraunhoffer lines, and the suppression of Raman scattering by water.

In the TIR bands, oil detectability derives from oil's different emissivity; its ability to absorb visible, and to retain thermal radiation in a manner different from water. Interference effects also can play a part.

The microwave portion of the spectrum is also used successfully to detect oil in the marine environment. Again, oil-to-water differences in emissivity, and also interference effects are used for target discrimination in passive microwave measurements. Surface roughness suppression by oil influences microwave emissivity and also its reflectance; the latter phenomenon is used for active radar surveillance of oil spills.

Most remote sensing devices operating in the (near-) visible spectrum conceivably can be used for imaging an oil slick. Film cameras are used because of their wide availability, users'

familiarity with the product, and the high spatial resolution of the photographs. Television cameras are becoming more popular because they are light and compact, and because the resulting images are available immediately. Multispectral scanners (MSSs) are more sophisticated, but less readily available. The two-channel version, operating in the ultraviolet and the TIR is a very useful and popular configuration because of the complementary role of these two bands in delineating the total slick and the thicker part of the slick, respectively. Human vision is by far the most widely used oil-reconnaissance system Despite its susceptibility to error, lack of performance at night or during adverse weather, and poor recording and hard-copy output, it is perceived to be reliable and most often is used as a quide for targetting electro/optical sensors.

Laser fluorosensors are, as yet, few in number, but offer a unique oil sensing capability that goes beyond detection to encompass precise three-dimensional mapping of oil slicks, as well as identification of basic oil types (Hoge and Swift, 1980; Buja-Bijunas et al., 1979; O'Neil et al., 1980c). As an active sensor, it can operate day or night, but is limited by clouds, fog, precipitation, etc. For oil-thickness measurement, the water Raman scattering suppression phenomenon is utilized; for oil type identification, the emitted fluorescence spectrum of the target is used for "fingerprinting".

In the thermal régime, passive infrared line scanners (IRLSs) are widely used (often in conjunction with an ultraviolet band) to map the thicker parts of the spill (O'Neil et al., 1980a), which are the main interest during slick clean-up or treatment activities. The scanner can provide a high-resolution (spatially and radiometrically) image that is quantitative and can be displayed in real time. Another option in the thermal band is the use of a TV-type device, which is currently approaching state-of-the-art status. The Canadian Offshore Oilspill Research Association (COOSRA) is now

considering the development of an ultraviolet and infrared combination, TV camera system for oil-spill surveillance. Such a system would have the advantage of simplicity in operation, lack of bulk and weight, and economy of purchase; and could be used as tactical support for an oil-spill response team, since its platform could be most any "aircraft of opportunity".

Both passive and active microwave devices can be applied successfully to the oil-detection problem. It has been shown (Croswell et al., 1981) that the dual-channel imaging microwave radiometer is useful for mapping thick (over 100 μm) oil films. This passive sensor has great potential for practical support during large oil-spill emergencies. Recent developments by the Technical University of Denmark (Nilsson and Skou, 1981) may bring this research device closer to commercial availability. Active microwave sensors, which have been used in oil-slick detection, are SLARs and microwave scatterometers. Of these, the real aperture SLAR may be the most practical because of its relative simplicity of architecture and operation, its lower cost (compared to SARs) and its wide swath of operation. Active radar sensors are operable day and night, and in most weather conditions. Their most serious limitations are lack of specificity to oil-caused slicks and reduced performance in calm water and oil-in-ice situations.

As indicated by several authors (Zwick et al., 1981; O'Neil et al., 1980d; INTERA, 1982; Kirby and Alföldi, 1983), no one sensor is suited for oil-slick detection under all conditions. Several sensors are required to cover a variety of possible environmental conditions, and also to corroborate and enhance each other's oil-detection abilities. A core package of sensors for detecting and mapping oil pollution has been recommended by a panel of technical experts (O'Neil et al., 1981). This package consists of: human observer, photographic cameras, SLAR, ultraviolet line scanner,

visible line scanner, IRLS and passive television. This configuration is, of course, ideal, and may not meet the criteria or budget of an operational marine surveillance agency.

In reality, a wide variety of "systems" is used around the world. In Canada, the Coast Guard uses visual observation and film cameras; Sweden, the Netherlands and Great Britain use a SLAR, ultraviolet/IRLS, and cameras; the USCG uses SLAR, ultraviolet/IRLS, film camera and an active-gated television system. The proliferation of these sensors is now prompting private industry to offer oil-spill (and general maritime) surveillance services on a commercial basis in several countries, including Canada, Denmark, Australia, Great Britain and the United States.

Research into sensor development and applications is also continuing. Using actual oil-spill events, as well as planned oil spills, several agencies in North America and Europe are attempting to establish optimum sensor and flight parameters for detecting marine oil slicks under varying environmental conditions. Large-scale events, such as the Arrow disaster (Gunard and Purves, 1970), the IXTOC oil-well blowout (Hayes, 1980), the Kurdistan incident (O'Neil et al., 1980b) and the breakages of the Amoco Cadiz (Fontanel, 1979) give excellent opportunity for sensor testing and exposing logistical problems in information transfer to decision makers (e.g., to the on-site commander of the oil-spill response team). Planned oil spills are usually very small, but the controls placed on the event make the scientific results much more valid and useful.

Two recent, controlled oil spills, in which remote sensing activities were prominent, were held off the New Jersey coast in November 1978 (O'Neil et al., 1980a) and off the eastern coast of Newfoundland in October 1981 (INTERA, 1982b; INTERA, 1982d). From such experiments, the theoretical and laboratory test of sensor performance was assessed under real environment conditons. Sensor

interrelationships and synergistic performance (for example, a profiling fluorosensor matched with an imaging scanner) could be evaluated so that well understood data from one instrument could be used to explain anomalies in data from another sensor (INTERA, 1982c).

In Europe, much of the remote sensing experimentation on oil-spill detection has centred on the Procedures International Standardized Oil Wake Experiment (ISOWAKE) concept. By international agreement, a set of standard procedures were established (by NATO) for oil wake discharges, such that an experiment could easily and accurately be repeated. The targets for ISOWAKE experiments are ships discharging oil, and the objective is to determine the rate of discharge. Some of these and other Europe-based experiments are tabled in Appendix B.

One of the best indicators for the maturity and sophistication of remote sensing technology is the level of reliance placed on it during legal proceedings against alleged oil polluters. This level will be linked directly to the demonstrated dependability of the sensor system and the resulting data in unambiguously reporting oil-slick and related phenomena. Visual observation by "experts" is often used in Canadian (and foreign) courts in aid of prosecution (see, for example, the Kungsholm incident [Canadian Federal Court, 1978]). The Swedish Coast Guard, on the other hand, has reportedly used remotely sensed and recorded data exclusively in prosecuting the originator of an oil spill; however, the regular use of electro/optical recordings of oil spills in Canadian courts is still several years away.

4.1.3 Satellite Methods

The prime advantages of satellite surveillance of oil spills are the wide-area synoptic coverage and the relatively low cost of data. Of the satellite systems in current operation, which may be considered for oil-slick detection, the trade-off between spatial and radiometric resolution becomes a more important criterion (INTERA, 1982a). Also, one of the frequently cited operational problems of satellites is the poor repetition (orbital) frequency, which determines revisit times and, therefore, dependability for coverage of any one point on the Earth's surface.

The National Oceanic and Atmospheric Administration (NOAA)/TIROS satellites are polar-orbiting, sun-synchronous, meteorological satellites operated by the U.S. National Environmental Satellite Service (NESS). The Advanced Very High Resolution Radiometer (AVHRR) carried on the current satellite offers approximately 1 km spatial resolution images in five spectral bands, positioned in the red, near-infrared and TIR spectral regions. One daytime and one nighttime overpass per day provide favourable frequency of coverage for most areas of North America and neighbouring ocean bodies. The spectral band positions and the spatial resolution, however, severely limit the utility of this system.

The LANDSAT series of satellites, also polar-orbiting and sun-synchronous, present the other end of the technical compromise. The MSS carried on each LANDSAT has four spectral bands in the green, red and near-infrared portions of the spectrum, operating at about 80 m resolution. The benefit of the high spatial detail and lower wavelength sensitivity is offset by the 18 day revisit frequency and generally low (64 level) radiometric resolution.

The new MSS instrument on LANDSAT IV, called the Thematic Mapper (TM), is as yet experimental, but promises better oil-spill imaging through its 256 level radiometry and seven spectral bands, which span most of the useful visible and infrared regions from 0.45 μm to 12.5 μm. The 16 day revisit time of LANDSAT IV, however, will make imaging of an oil spill a fortuitous event.

LANDSAT MSS has imaged the very large oil slick in the Gulf of Mexico resulting from the IXTOC-I oil well blowout in 1979. Deutsch et al. (1980) found oil-slick features on 185 MSS scenes, and performed contrast-stretching on some data sets, in attempts to enhance visibility of the slick. Suppression of solar specular reflection by oil-dampened waves was posited as a prime factor in the development of oil-to-water contrast on the MSS images. Quantitative analyses on an IXTOC oil-slick scene were later conducted (INTERA, 1982a) with colorimetric and calibrated spectral techniques, in attempts to: 1) separate oil from false oil targets; 2) define detail within the oil slick; and 3) establish repeatable methods for oil identification.

Many slick-like features have been observed on LANDSAT MSS images from around the world (Deutsch, et al., 1977; Deutsch and Estes, 1980), but positive identification has only been through prior knowledge of a slick's location. Perhaps the value of satellite reconnaissance of oil spills comes from discerning slick artifacts, which makes the airborne or surface identification of these features much faster and economical.

The oil slick from the Kurdistan incident was studied on satellite imagery (Dawe et al., 1981; INTERA, 1982a), but the poor illumination due to low sun angles (37° elevation) provided no evidence of oil on water. Oil on an ice background was located on LANDSAT MSS imagery, due to the high contrast afforded by these two features. Prior knowledge of the location of the oil-contaminated ice

was instrumental in this deduction. Low sun angles also were the prime factor in preventing conclusive analysis of the Scott Inlet oil seep (Kirby, 1979; INTERA; 1982a).

SARs on satellite platforms are a promising source of oil-spill data. Their relatively high resolution, cloud penetration and day/night operation bring a greater utility to satellite surveillance. The SEASAT SAR has been analysed for this prospective role (Apel and Brown, 1981), and the prospective Canadian RADARSAT may provide such service. As with airborne radars, satellite-borne SAR instruments will labour under the limitation of requiring the capability of imaging sea clutter, before sea clutter suppression by oil slicks can be detected.

As noted by several authors (Alvarado et al., 1979; O'Neil et al., 1980a; INTERA, 1982a), the key to the practical and effective use of satellite-derived data on oil spills is the timeliness of access to that information by the spill response team. Real-time, or near-real-time data reduction of currently operating environmental satellite sensors is feasible (INTERA, 1982a) and is a vital logistic that must be designed into the ground segment of future satellite programs for support of oil-spill (and other) emergencies.

4.2 SUBSURFACE AND DISSOLVED OIL IN WATER

The complex process of weathering will force an oil slick to undergo various physical and chemical changes. Natural processes, such as dissolution, oxidation, evaporation and emulsification, will cause significant alteration of the make-up, appearance, cohesion and mobility of an oil slick. The subsidence of a slick below the water surface, the formation of water-and-oil emulsions, and the development of sinking tarballs are well known phenomena (Fingas et al., 1979). Subsurface oil was detected, for instance, near the IXTOC-I blowout in the Gulf of Mexico (Walter and Proni, 1980) and at the site of the

Kurdistan incident (O'Neil et al., 1980b). Without doubt, the detectability and identification of oil located below the water surface is a more difficult task.

4.2.1 Surface Methods

Practical experience in the detection of subsurface oil is limited. Mechanisms for this process are primarily an adaptation of methods for surface oil detection, with the notable exception of acoustic sounding techniques.

If electromagnetic radiation (EMR) is used as the medium for detection, then it is safe to say that oil-detection confidence is in inverse proportion to increasing depth of the oil below the surface. This generalization comes from the fact that EMR will be attenuated more as its path through the water column is increased, reducing the target's signal-to-noise ratio (S/N). A useful analogy for this situation is the increasing difficulty of visual observation of features within water, as these features tend further below the surface.

It may be possible to enhance the visibility of subsurface oil, depending on conditions at a particular spill site. The use of polarized optics (glasses, filters, etc.) by an observer can produce the well known effect of better visibility of underwater features, by reducing the surface glare. Thus, target-to-background contrast is increased. For nighttime reconnaissance, the use of fluorescence techniques (such as those described in Section 4.1.1) may have limited use in detecting oil which is just below the water surface. Any substantial depth of the oil would render these fluorescence methods impractical, due to the water attenuation of both the downwelling excitation radiation and the upwelling fluorescence emission.

Acoustic techniques have been in regular use for identifying and mapping a wide variety of marine phenomena. In a controlled oil-spill exercise off the coast of Massachusetts in September 1981, acoustic sensing gear was used successfully on board a research ship to detect subsurface oil and to monitor its progress through the water (Bannister et al., 1982). The instrument was a dual-channel transceiver, operating between 3 KHz and 300 KHz, and employing a transducer vehicle towed behind the ship (Datasonics, 1983). During the spill trials, the operators of the acoustic gear were able to identity ". . . globular material near the surface of the water in the precise vicinity of the spill." At a later time, this instrument recorded ". . . enhanced sonar signals from globular material descending from the surface."

Another exercise using acoustic sounding techniques was similarly successful in subsurface oil detection. During a cruise into the site of the IXTOC-I oil spill in the Gulf of Mexico in September 1979, researchers from the (U.S.) NOAA used high-frequency acoustic instrumentation to define subsurface oil. They concluded, from extensive tests with 20 KHz acoustics, that subsurface oil can be detected, and that the operable depth of this technique is at least 20 m.

4.2.2 Airborne Methods

Airborne methods of subsurface oil detection can conceivably utilize the acoustic methods described in the previous section (4.2.1), since acoustic surveillance by immersion instruments towed by helicopter is a feasible concept. Most methodologies for this problem, however, employ remote sensing by EMR. Some EMR forms do not penetrate appreciably into the water column. Thus, instruments such as TIR scanners and microwave devices (passive radiometers, scatterometers, side-looking radars) cannot be used for subsurface oil detection.

Potentially useful instrumentation works in the ultraviolet and low-wavelength visible bands for water penetration. Thus, candidate systems include human observers, film cameras, television cameras, laser fluorosensors and scanners/radiometers. These are all subject to the previous cautions expressed for light attenuation by the water that intervenes between the sensor and the oil target. Particular care must be exercised to define optimum water penetration for the system in use, by choosing/filtering those spectral bands which permit best water penetration, and by reducing surface reflection through polarization techniques and/or a choice of illumination/ viewing geometry.

4.3 OIL ON ICE

4.3.1 Surface Methods

Direct observation appears to be the only practical means of reconnaissance for oil on the ice surface, from a vantage point on the Earth's surface. Surface vehicles are not liable to be used for extensive oil-on-ice search programs, but there may be a requirement for (perhaps) a ship to find and deal with oil-contaminated ice. Again, the circumference of visibility is reduced for an observer on the surface, and the oblique view of a target promises additional problems of detection. The catalogue of visual features of oil on ice compiled from the air during the Kurdistan incident (Reimer, 1980), as described in the next section (4.3.2) are, to a large extent applicable to surface observation as well.

4.3.2 Airborne Methods

Oil on ice may be considered to be a target of higher contrast than on a water background, and therefore, easier to detect. This is not necessarily true, since the complex shapes, reflectivity and shadowing of ice would hinder, rather than help the definitive

identification of oil. In such a complex environment, where all forms of information must be assessed (texture, albedo, position, hue, etc.), the human eye/brain combination may be successful in assimilating target-specific and contextual data to arrive at useful decisions.

The best known example of visual aerial reconnaissance over an extensive oil-in-ice spill is the Kurdistan incident of 1979, when a large amount of Bunker C oil was entrained in pack ice near the northeastern shore of Nova Scotia. The crew of two aircraft from CCRS (O'Neil et al., 1980b) used visual observation and identification to guide the aircraft, with its vast array of remote sensing devices, over oil targets.

The Centre for Cold Ocean Resources Engineering (C-CORE) of Newfoundland carried out extensive aerial reconnaissance and constructed a catalogue of visual features related to the appearance of the ice-entrapped oil (Reimer, 1980). Colour line and saturation, shape and size, brightness, and the positional relationship of the oil with different ice types were used to inventory and classify the various oil-and-ice features. A very useful part of the report included a listing of probable false targets, such as inorganic sediment on/in the ice, ice patterns in streaks and whorls, organic materials on/in the ice, and suspended solids carried by river outfalls or stirred up from the ocean bottom. The best distinguishing features, by which an observer might separate these false targets from true oil features, were also detailed.

The experience from the Kurdistan incident has prompted several recommendations by CCRS (O'Neil et al., 1980b) on the utility of various remote sensing devices for detecting oil in ice. CCRS identifies the laser fluorosensor as an instrument that may detect and identify, with great reliability, oil on water, on ice, and washed up on shore. The ultraviolet/TIR scanner is said to be useful, but

can be confused by false targets such as soil on the ice. Operating in the ultraviolet and visible wavelength, film cameras and (low-light-level) television cameras are promising sensors, although film processing requirements remove film cameras from a real-time reconnaissance role. SLAR is promoted as very useful over open water, but not for oil on ice, a recommendation echoed by the results of a study on the topic by C-CORE (1980, 1981).

4.3.3 Satellite Methods

As with oil on water, satellite surveillance of oil on ice suffers from inherent problems of poor satellite revisit frequency and limited spatial, spectral and radiometric resolution. Nevertheless, it has been used at least once — in the Kurdistan incident — to image oil entrained in ice (Dawe et al., 1981; INTERA, 1982a). LANDSAT MSS imagery was used for this purpose; however, the analysts had to use prior knowledge to locate the oil-contaminated ice, since the MSS could not describe a unique spectral fingerprint for oil, and therefore, would image false targets as well.

The low illumination levels experienced at high latitudes, in which marine ice is prevalent, demand the use of high-sensitivity instruments. Although not ideal, the LANDSAT IV TM with its 256 level radiance scale per spectral band (and 30 m spatial resolution) extends oil detection to a certain degree. The more conventional, low-resolution MSS should be used in the high gain mode (Alföldi et al., 1978; INTERA, 1982a) for optimum performance.

Experimentation is required with the TIR-sensitive bands of the TM to determine whether temperature differences between oil and ice can be detected. The absorption by oil of solar radiation may raise the oil temperature sufficiently to provide a detectable contrast between oil and ice. Otherwise, sufficient contrast must be generated by differences in oil and ice emissivity. Satellite-borne (active) radar is not expected to be useful for detecting oil on/in/under ice.

4.4 OIL UNDER OR IN ICE

Undersea oil well blowouts or pipeline leaks are just some of the more obvious ways in which oil could be released into the ocean and under an ice cover. Oil will rise in a water column and fill the bottom topography of floating ice. It will then move with the ice and, if possible, rise through cracks in the ice. The possibility exists, therefore, that spilled oil may have to be detected under or in ice.

This branch of oil detection is not well developed as yet, although its application may be critical during an oil-spill emergency in the Arctic. Research is now under way in several promising areas.

4.4.1 Surface Methods

A great variety of methodologies and instruments has been turned towards the problem of detecting oil under ice. REMOTEC (1981) reported attempts at using gamma-ray spectrometry, impulse radar methods, active radio frequency techniques and active acoustic sensing. Only the last of these was (partly) effective (Parashar et al., 1981). In an earlier series of evaluations NORDCO (1979) described possible sensing instrumentation for radio frequency, acoustic, optical, nuclear and gas sniffer methods of oil-under-ice detection. It was found that optical and gas sniffer techniques would nct be applicable, while nuclear methods would be severely limited. Some promise was indicated for the radio and acoustic technology.

Recent work by Jones and co-workers (1982) has centred on the use of ultrasound for detecting an oil layer trapped between sea ice and seawater. Both theoretical and empirical studies have pointed to going beyond simple reflection measurements, towards exploiting interfacial effects among the various media in question. The attenuation and propagation characteristics of transverse and

compression waves by the viscous (oil) and non-viscous (ice) media may be the key to oil detectability. Instrumentation development and field testing, sponsored by Canadian industry and government, are now under way to establish the practicality of this approach.

4.4.2 Airborne Methods

The use of airborne sensors incorporating laser devices is being tested in at least two research organizations for possible use in detecting oil under ice. One experiment involves the penetration of ice by laser-produced radiation and the subsequent excitation of sub-ice oil. Detection of the resulting fluorescence emission by the oil has been detected for an ice thickness of approximately 2 m (personal communication, R. Goodman, Esso Resources Ltd.). In a different approach, C-CORE (Laidley, 1981) is attempting to raise the temperature of oil (in ice), using a CO_2 laser so that it is in thermal contrast to its surroundings (ice, water). A TIR-sensitive instrument would then provide the detection function. A low-flying helicopter is envisioned as a suitable platform.

In an even more promising line of research, impulse radar techniques are being investigated for their special abilities to penetrate ice and detect sub-ice oil (Mann, 1979; Dean, 1981). To be studied are phenomena related to the insulation properties of oil, dielectric effects (phase change of reflected radiation) and constructive interference (thin film effects; Jackins et al., 1982). Impulse radar methods, if practicable, may be one of the very few techniques of efficient aerial surveillance for oil under ice.

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7. APPENDICES

7.1 APPENDIX A: EUROPEAN AGENCIES DEALING WITH OIL-SPILL RESEARCH AND OPERATIONS

7.1.1 National Agencies and Laboratories

1. Belgium:

a. National Contact: Secretariat d'Etat à l'Environnement
Att. Dr. Georges Pichot
Manhattan Centre, Tower H2
B-1010 Brussels
Phone: 32-(02) 2191880 ext 698
Telex: 41746 ENVIRO B

2. Denmark (and Greenland)

a. National Contact: National Agency for Environmental Protection (Miljostyrelsen)
Att. Cdr. P. Stamp, Chief
Nyropsgade 47
DK-1401 Copenhagen K
Phone: 45-(01) 578310
Telex: 31209 MILJOE DK

b. Hardware Research: Technical University of Denmark
Att. Dr. Niels Skou
Electromagnetics Institute
DK-2800 Lyngby
Phone: 45-(02) 881444
Telex: 37529 DTHDIA DK

c. Hardware and Modelling Development:

Danish Hydraulic Institute
Att. Mr. R. Zorn
Agern Alle 5
DK-2970 Horsholm
Phone: 45-(02) 868033
Telex: 37402 DHICPH DK

d. Operations Research:

INTRADAN Environmental Consultants A/S
Att. Mr. B. Møller Sørensen, President
Vejlevangen 5
P.O. Box 122
DK-5300 Kerteminde
Phone: 45-(09) 323647
Telex: 50310 NORDAN DK

3. Finland:

a. National Contact:

Finnish Coast Guard
Att. Dr. R. Sorvali/Dr. R. Sandelin
P.O. Box 3
SF-00131 Helsinki 13
Phone: 358-(0) 1612022
Telex: 124865 RVLE SF

4. France:

a. National Contact:

Ministère de la Qualité de la Vie
DPPN-SPMO
Att. Mr. J.M. Massin
14, boul. du General Leclerc
F-952521 Neuilly/Seine
Phone: 33-(01) 7581212
Telex: 620602 DENVIR F

b. Experimental Research:

Institut Français du Petrole (IFP)
Att. Mr. A. Wadsworth
B.P. 311
F-92506 Rueil-Malmaison
Phone: 33-(01) 7490214 ext 2367/2294
Telex: 203050 IFP F

c. Sensor Development and Operations:

Laboratoire National d'Essais
Att. Mr. R.A. Burkhalter
1, rue Gaston Boissier
F-75015 Paris
Phone: 33-(01) 5322989
Telex: 202319 F

5. Germany (Federal Republic):

a. National Contact:

Bundesministerium fur Verkehr
Att. Herr Oberregierungsrat Smid
D-5300 Bonn
Bertha-Von-Suttner-Platz
Phone: (0) 228 3004325
Telex: 885700 BMV D

b. Oil Behaviour Research:

Bundesanstalt fur Gewasserkunde
Att. Mr. F. Gunneberg, Director
Postfach 309
D-5400 Koblenz
Phone: 49-(0261) 12431
Telex: 862499 BAFGK D

c. Hardware Research:

University of Oldenburg
Att. Prof. J. Luther
FB 4 - Experimental physik
D-2900 Oldenburg
Phone: 49-(0441) 7981
Telex: 25655 UNOL D

d. In Situ Oil Behaviour Research:

Universitat Hamburg
Att. Dr. H. Huhnerfuss
Institute of Organic Chemistry
Martin-Luther Kin Platz 6
D-2000 Hamburg 13
Phone: 49-(040) 4123-4240
Telex: 214732 UNIHH D

e. Operations Research:

Deutsche Hydrographisches Institut
Dr. H. Weidemann
Bernhardt-Nocht Strasse 78
Postfach 220
D-2000 Hamburg 4
Phone: 49-(040) 3190-5148
Telex: 211138 BMVHH D

6. Great Britain:

a. National Contact:

Department of Trade
Att. Dr. D. Cormack
Sunley House
90/93 High Holborn
London WC1V 6LP
Phone: 44-(01) 4056911 ext 480
Telex: 264084 MARBOT G

b. Multipurpose Research:

Warren Spring Laboratory
Att. Dr. P. Morris
Gunnes Wood Road
Stevenage, Herts SG1 2BX
Phone: 44-(0438) 3388
Telex: 82250 G

7. Italy:

a. Operations Research:

CNR - Laboratorio Dinamica Grande Masse
Att. Dr. L. Alberotanza
S. Polo 1364
I-30125 Venice
Phone: 39-(041) 705677
Telex: 41095 I

8. Netherlands:

a. National Contact:

Rijkswaterstaat - North Sea Directorate
Att. Mr. W. Wijmans
Nijverheidsstraat 1
Rijswijk 2288 BB
Phone: 31-(070) 949500
Telex: 33782 RWSN2 NL

b. Laboratory Research on Oil Fluorescence:

T.N.O. - Institute of Applied Physics
Att. Dr. H. Visser/Mr. C. Smorenburg
P.O. Box 155
2600 AD Delft
Phone: 31-(015) 569300
Telex: 38091 TPDDT NL

9. Norway:

a. National Contact:

State Pollution Control Authority
Att. Dr. Flikke
P.O. Box 8100, Oslo Dep.
Oslo 1
Phone: 47-(2) 229810
Telex: 76684 N

b. Hardware Research: Christian Michelsen's Institute
Att. Mr. T. Gytre
Fantoftevegen 38
N-5036 Fantoft
Phone: 47-(05) 284410

10. Spain:

a. Research: Centro Nacional de Investigaciones Pesqueras
Att. Prof. A. Ballester Nolla
Paseo Nacional s/n
Barcelona - 3
Phone: 34-(093) 3106450
Telex: 59367 INPB E

11. Sweden:

a. National Contact: Swedish Coast Guard
Att. Commodore Sven Uhler
P.O. Box 2267
S-10316 Stockholm
Phone: 46-(08) 240015
Telex: 17982 Coastg S

b. Sensor Research: Swedish Space Corporation
Att. Mr. Lars Backlund
Tritonvagen 27
S-17154 Solua
Phone: 46-(08) 980200
Telex: 17128 Spaceco S

c. Sensor Research: Technical University of Lund
Att. Prof. S. Svanberg
S-2207 Lund 7
Phone: 46-(08) 124600

7.1.2 International Research Organizations

1. CONCAWE (the Oil Companies International Study Group for Conservation of Clean Air and Water)
   Att. Dr. J.H. Somerville
   Babylon - Kantoren A
   Koningin Julianaplein 30-9
   2595 AA The Hague
   The Netherlands
   Phone: 31-(070) 475494
   Telex: 31005, c/o SIPM NL

2. Joint Research Centre - Ispra Establishment
   (of the Commission of the European Communities)
   Att. Mr. G. Fraysse/Prof. G. Bertolini
   I-21020 Ispra (Va)
   Italy
   Phone: 39-(0332)-780131
   Telex: 380042 EUR I

7.1.3 International Organizations Based in Europe, Acting Against Oil Pollution

1. United Nations Environmental Programme (UNEP)
   Att. Dr. Stjepen Keckes/Dr. M. Elder
   Palais des Nations
   CH-1211 Geneva 10
   Switzerland
   Phone: 41(022) 985850 or 988400
   Telex: 28877 GENEVA CH

2. Regional Oil Combatting Center (ROCC)
   Att. Dr. Philippe de Lourd
   Manoel Island
   Malta
   Phone: 37296
   Telex: 464 UNROCC MW

3. International Maritime Organisation (IMO)
   4 Albert Embankment
   London SE1 7SR
   England
   Phone: (01) 735 7611
   Telex: 23588 G

   a. Industry & Environment Office:
      17 rue Margueritte
      75015 Paris
      France
      Phone: (33-1) 766 1640 or 227 4512
      Telex: 650273 F

   b. Regional Seas Programme Activity Centre:
      Palais des Nations
      1211 Geneva 10
      Switzerland
      Phone: (41-22) 985850
      Telex: 28877 CH

4. International Assocation of Independent Tanker Owners (INTERTANKO)
   P.O. Box 1452 - VIKA
   Radhusgaten 25
   Oslo 1
   Norway
   Phone: (47-2) 416080
   Telex: 19751 N

5. International Chamber of Shipping (ICS)
   30-32 St. Mary Axe
   London EC3A 8ET
   England
   Phone: (01) 283 2922
   Telex: 884008 G

6. International Oil Pollution Compensation Fund (IOPC Fund)
   1-4 Yarmouth Place
   London W1Y 70W
   England
   Phone: (01) 493 6932
   Telex: 23588 G

7. International Petroleum Industry Environmental Conservation Association (IPIECA)
   1 College Hill
   (1st Floor)
   London EC4R 2RA
   England
   Phone: (01) 248 3447/8
   Telex: 883281 G

8. International Tanker Owners Pollution Federation Limited (ITOPF)
   Staple Hall
   Stonehouse Court
   87/90 Houndsditch
   London EC3A 7AX
   England
   Phone: (01) 621 1255
   Telex: 887514 G

9. Offshore Pollution Liability Association Limited (OPOL)
   5th Floor
   Cleveland House
   19 St. James's Square
   London SW1Y 4LT
   England
   Phone: (01) 839 7141
   Telegrams: c/o HAMBROIL London SW1

10. Marine Pollution Compensation Services Limited (CRISTAL)
    Staple Hall
    Stonehouse Court
    87/90 Houndsditch
    London EC3A 7AB
    England
    Phone: (01) 621 1322
    Telex: 888043 G

11. Oil Companies International Forum (OCIMF)
    6th Floor
    Portland House
    Stag Place
    London SW1E 5BH
    England
    Phone: (01) 838 7696 or 828 6238
    Telex: 24942 G

12. Oil Industry International Exploration & Production Forum (E & P FORUM)
    3rd Floor
    37 Duke Street
    London SW1Y 6DH
    England
    Phone: (01) 930 6602
    Telex: 919707 G

13. Protection & Indemnity Clubs (International Group of P & I Clubs)
    1 Pepys Street
    London EC3N 4AL
    England
    Phone: (01) 480 7272
    Telex: 886029 or 886688 G

14. Institute for Industrial Research and Standards
    Ballymun Road
    Dublin 9
    Ireland
    Phone: (01) 370101
    Telex: 5449 IIRS, EI

7.2 APPENDIX B: RECENT EUROPEAN REMOTE SENSING OIL-SPILL EXPERIMENTS

The following table (Sørensen, 1983) indicates recent, experimental oil-spill activities by European agencies.

Table 7.1. Recent European remote sensing oil spill experiments (Source: Sørensen, 1983)

DATE	OIL SPILL EXPERIMENT	PLACE AND POSITION	QUANTITY OF OIL SPILLED	AIRBORNE SENSORS USED	COORDINATING AGENCY FROM WHERE RESULTS CAN BE OBTAINE
July 1 + 2, 1981	ISOWAKE	Southern Bight of the North Sea. 52°00'N - 3°00'E	ISOWAKE Standard	2 SLARs, 1 DCLS	Joint Research Centre - Ispra Establishment Att. S. Galli de Paratesi
November 17-29, 1980	Sensor Tests	Southern Bight of the North Sea 52°05'N - 3°15'E	ISOWAKE Standard	2 SLARs, 1 DCLS	Rijkswaterstaat - North Sea Directorate Att. W. Wijmans
May 13, 1982	Microwave Radiometer Test	Kattegat (north of Denmark) 57°57'N - 10°29'E	7 tons of heavy fuel and ISOWAKE Standard	2 SLARs, 1 DCLS 1 MW radiometer	Danish Agency for Environmental Protection Att. Cdr. P. Stamp
July 14, 1981	Sensor Tests	Southern Bight of the North Sea 52°30'N - 2°30'E	ISOWAKE Standard	1 SLAR, 1 IRLS	Warren Spring Laboratory Att. N. Hurford
September 20-21, 1982	Sensor Tests	Mediterranean Sea (Toulon) 42°30'N - 6°E	2 x 5 m3 (day 1) 3 x 5 m3 (day 2)	1 MWR, 1 SLAR, 1 IRLS, Cameras	Joint Research Centre - Ispra Establishment Att. R. Gillot
October 27, 1982	Sensor Tests	German Bight of the North Sea 54°20'N - 7°40'E	ISOWAKE Standard	1 MWR, 1 SLAR, Cameras	Bundesanstalt für Gewässerkunde Att. F. Gunneberg Postfach 309, D-54 Koblenz, Ger
July 25-31, 1982	Oil Drift, Dispersion and Weathering	Norwegian Atlantic Coast 65°N - 7°30E	100 tons	1 SLAR, Camera	Norwegian State Pollution Control Authority Att. A. Flikke

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Table 7.1. Concluded.

DATE	OIL SPILL EXPERIMENT	PLACE AND POSITION	QUANTITY OF OIL SPILLED	AIRBORNE SENSORS USED	COORDINATING AGENCY FROM WHERE RESULTS CAN BE OBTAINED
Medio October, 1983	Sensor Tests	Southern Bight of the North Sea 52°00'N - 3°00'E	Undecided	2 MWRs, 2 SLARs, 1 DCLS, 1 tunable LFS	Joint Research Centre - Ispra Establishment Att. R. Gillot
April 28, 1982	Test of Oil Pollution Combatting Systems	North Sea - Ekofisk Exploration Field 56°30'N - 3°15'E	>100 tons	2 SLARs	Norwegian State Oil Pollution Authority Att. A. Flikke
September 1978	Drift and Dispersion	Tromsø, North Norway 71°30'N - 19°E	30 tons	1 SLAR, camera	Norwegian State Oil Pollution Authority Att. A. Flikke

Note: SLAR -- side-looking airborne radar
DCLS -- dual-channel line scanner
MWR -- microwave radiometer
IRLS -- infrared line scanner
LFS -- laser fluorosensor